Deep-Subthreshold η and π^0 Production Probing Pion Dynamics in the Reaction Ar + Ca at 180A MeV

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(Received 25 June 1998)

We report on a measurement of subthreshold η and π^0 mesons in the reaction Ar + Ca at 180A MeV. We find that the ratio of the η to π^0 meson-production cross section is more than a factor of 20 smaller than the one expected from threshold-energy scaling of meson production. In addition, the multiplicity of high m_t π^0 increases faster with the centrality of the reaction than the multiplicity of the bulk of π^0 mesons. This behavior is explained by the rescattering of π mesons in nuclear matter at the origin of most energetic particles.

PACS numbers: 25.75.Dw

Heavy-ion collisions offer the opportunity to study in the laboratory the properties of nuclear matter under extreme conditions of temperature and density. The creation of particles like photons, mesons, di-leptons, or antibaryons below the free nucleon-nucleon energy threshold represents a powerful probe of such excited states of nuclear matter [1–4]. The observation of deep-subthreshold particles, such as photons [5], η mesons [6], and $K^{+,-}$ [7,8] for which the energy represents a sizable fraction of the total energy available in the system, raises the question of how a highly excited and dense system of interacting fermions can concentrate a significant amount of the available energy in the creation of a single energetic or massive particle. Since the appropriate coupling of the nucleon Fermi momenta with the momentum of the relative motion falls short of providing the energy necessary to create such particles, higher order processes beyond the nucleon-nucleon inelastic collisions, like secondary interactions of pions and resonances, should play a major role [5,7]. Deep-subthreshold particle production hence probes the strong interaction processes among nucleons, baryonic resonances, and mesons, possible only in a dense and excited phase of nuclear matter. In this respect, the present experiment aims to investigate simultaneously the subthreshold and deep-subthreshold particle production in heavy-ion collisions at a fixed bombarding energy through the measurement of π^0 and η meson-production properties. The threshold energies in free nucleon-nucleon collisions for the production of π^0 and η mesons are 280 MeV and 1255 MeV, respectively. The system studied was Ar + Ca at 180A MeV where the η mass represents 17% of the total available energy and the π^0 mass 4%.

The ^{40}Ar beam was delivered by the heavy-ion synchrotron SIS at GSI, Darmstadt, with an average intensity of 5×10^8 particles in spills of about 9 s. The total number of accumulated beam particles was 4×10^{13}. The calcium target was 320 mg/cm^2 thick. A start detector (SD) [9] consisting of 32 NE102 plastic scintillators surrounding the target at a distance of 101 mm signaled the occurrence of a reaction and delivered the start signal for time-of-flight measurements. In addition the number of detected particles in the SD, M_{SD}, was used as a measurement of the reaction centrality. The SD efficiency averaged over the impact parameter, $\langle \epsilon_s \rangle_b$, was estimated from GEANT simulations [10,11] using the FREESCO event generator [12]. We found $\langle \epsilon_s \rangle_b = 0.56$ for the reaction Ar + Ca at 180A MeV. The averaged SD efficiency when a π^0 is produced was calculated by weighting the impact-parameter distribution with the distribution of the number of participants $A_{\mathrm{part}}(b)$ [13]. We found $\langle \epsilon_s \rangle_{A_{\mathrm{part}}(b)} = 0.90$. The reaction rate measured with SD was $p_s = 6.9 \times 10^{-3}$ per beam particle. The TAPS multidetector [14] was used for photon detection. The 384 TAPS modules were assembled in six blocks of 8×8 detectors, mounted in two symmetric towers of three blocks each [15]. The towers were positioned at $\theta = \pm 70°$, 80 cm away from the target, on each side of the beam direction, covering the mid-rapidity

 0031-9007/99/83(8)/1538(4)$15.00

region, $0.26 < y/y_{\mathrm{beam}} < 0.71$. Neutral mesons were identified in TAPS by their electromagnetic decay into two photons.

The most energetic photons ($E_\gamma > 100$ MeV), which develop spatially large electromagnetic showers, were selected by the detection of at least two neutral hits in the same block (a neutral hit is defined as a signal in the BaF_2 crystal with a deposited energy of at least 10 MeV without a coincidence from the corresponding charged-particle veto detector). Therefore, to enhance events with η mesons we require two neutral hits in one block of the left tower in coincidence with two neutral hits in one block belonging to the right tower. As a trigger for π^0 mesons, we required two neutral hits in one TAPS block in coincidence with two neutral hits in any other TAPS block. In addition, a minimum-bias π^0 trigger was defined by requiring a neutral hit in two blocks. These triggers were validated with a minimum-bias SD trigger.

Electromagnetic particles were discriminated against hadrons via time-of-flight, BaF_2 pulse-shape analysis, and anticoincidence with the corresponding charged-particle veto detector [15]. The energy calibration of the BaF_2 crystals was based on the energy loss from cosmic muons. Photon energy and direction were reconstructed from the electromagnetic shower using a cluster algorithm [16]. The invariant mass of identified photon pairs was calculated by the relation $M_{\mathrm{inv}}^2 = 2E_1E_2(1 - \cos\theta_{12})$, where $E_{1,2}$ are the corresponding photon energies and θ_{12} the relative angle. The invariant-mass distribution (Fig. 1a) is dominated by the characteristic of the π^0 mass peak. The combinatorial background, calculated around the π^0 peak using the event-mixing technique [17], represents only a few percents of the total yield. For η enriched events, photons with energies above 140 MeV are identified based on the analysis of the shower topology [15]. Within these trigger conditions the π^0 mass peak is suppressed in our detector acceptance (see Fig. 1b). The resulting invariant-mass distribution exhibits a discontinuity in the region of the η mass and deviates from the smooth calculated combinatorial background. This deviation is identified with an excess of events attributed to the two photon decay of the η meson. The number of integrated events after background subtraction is nine, twice the statistical error. Thus, this number of events is compatible with a value larger than zero within a confidence level of 97%. The observed yield represents a cross section of 19(10) nb in the rapidity window that we consider as an upper limit for the production of η mesons in the reaction Ar + Ca at 180A MeV.

The acceptance corrected π^0 transverse-mass, m_t, distribution (Fig. 2) exhibits an exponential behavior between 180 and 400 MeV with an inverse slope of $T = 24(1)$ MeV in agreement with the systematics [18]. In the present measurement, the m_t distribution for π^0 extends to well above E_{max}, calculated as the available energy in a single nucleon-nucleon collision when the intrinsic momentum is parallel to the beam momentum and

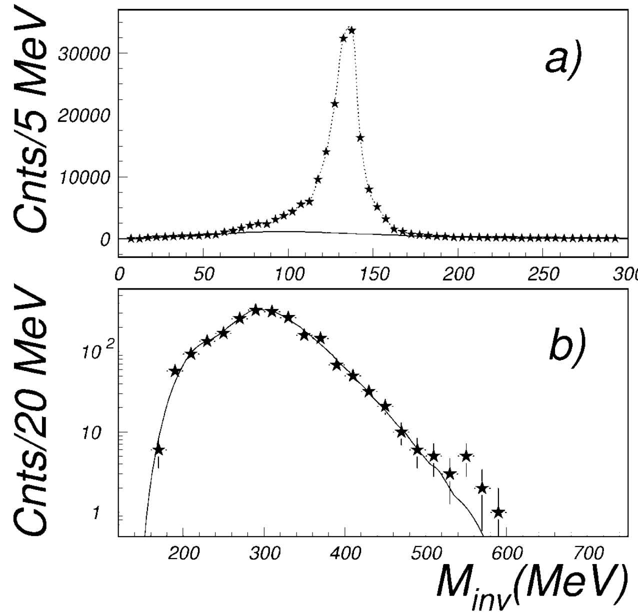

FIG. 1. Two-photon invariant mass spectrum in the reaction Ar + Ca at 180A MeV. Solid lines represent the combinatorial background calculated by the event-mixing technique [17]. (a) The π^0 trigger and (b) the η trigger for photon energies larger than 140 MeV applying the electromagnetic shower discrimination based on the topology shower analysis [15].

equal to the Fermi momentum of infinite nuclear matter ($p_F = 270$ MeV/c and $E_{\mathrm{max}} = 300$ MeV at 180A MeV) [5]. To take into account the specific hardness of the most energetic π^0, the two-component expression $(p_0 + p_1 m_t)\exp(-m_t/M_1) + p_2\exp(-m_t/M_2)$ was fitted to the m_t spectrum between 140 and 600 MeV (Fig. 2). We obtain $p_0 = -0.202(0.023)$ mb/MeV^3, $p_1 = 1.5(0.2) \times 10^{-3}$ mb/MeV^4, $p_2 = 1.23(1.0) \times 10^{-7}$ mb/MeV^3, $M_1 = 18(1)$ MeV, and $M_2 = 54(7)$ MeV. Using this expression we have extrapolated the π^0 differential cross section in the η m_t region (Fig. 2). With such a prescription, we find that the π^0 cross section for $m_t > M_\eta$ is 28(20) nb, and we measure $\sigma_\eta^{\Delta y} \leq 19(10)$ nb. Therefore, the measured yields are not inconsistent with the meson m_t scaling observed at higher energies [6,19,20].

The extrapolation to 4π of meson cross sections has been performed [11] assuming an isotropic emission from a quasithermal source in the NN center-of-mass frame. The pure thermal emission was modified at low energies to reproduce the experimental π^0 spectrum (see Fig. 2), following the previous parametrization of the m_t distribution. A pure thermal emission would increase by 17% the neutral pion efficiency, $\epsilon^{4\pi}$, reported in Table I. We deduce a ratio between π^0 and η cross section smaller than $3.0(1.5 \times 10^{-6})$ (see Table I), a value more than 20 times smaller than the value deduced from the systematics of NN threshold-energy scaling [21,22]. This scaling on the NN threshold energy E_{NN}^{th} predicts that the meson multiplicity is independent of the meson nature

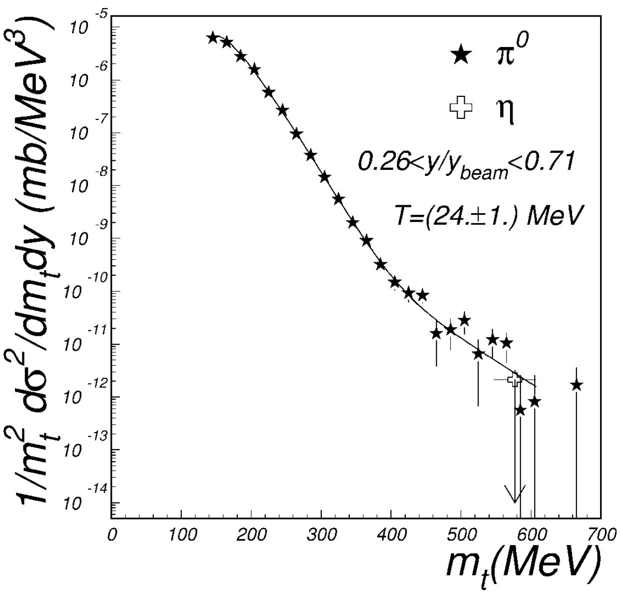

FIG. 2. Transverse mass distribution of π^0 and η mesons corrected by m_t-y acceptance in the rapidity window $0.26 < y/y_{\rm beam} < 0.71$. A one-component fit between 180 and 400 MeV gives an inverse slope parameter $T = 24(1)$ MeV. The solid line represents a fit between 140 and 600 MeV. Errors include statistical and systematic errors coming from combinatorial background subtraction and from reaction efficiency of the start detector.

for a given ratio $f = E_{\rm beam}/A_{\rm proj}/E_{NN}^{\rm th}$. This scaling has been observed between $\pi^0$and η mesons at near-threshold energies ($f \sim 0.5$–1.0) [6,20,21]. However, the η meson multiplicity at 180A MeV ($f_\eta = 0.14$) is more than 1 order of magnitude lower than the π^0 multiplicity at the corresponding energy (40A MeV, $f_\pi = 0.14$) [23,24].

To gain more insight into the meson-production mechanism beyond $E_{\rm max}$, we have studied the π^0 multiplicity as a function of the reaction centrality (Fig. 3). The π^0 multiplicity increases with $M_{\rm SD}$ as a consequence of the increase of the number of participants. Moreover, multiplicity of high m_t π^0 ($m_t > 300$ MeV) rises faster. We have fitted the evolution of the multiplicity with the number of detected particles by the expression $M_0 \exp(-M_{\rm SD}^0/M_{\rm SD})$, and we found $M_{\rm SD}^0 = 1.04(0.08)$ for the bulk of π^0 and 1.32(0.12) for the high m_t π^0 ($m_t > 300$ MeV). This observation can be explained by a geometrical model assuming that the most energetic particles accumulate their energy through multiple interactions with the nuclear medium. We assume that the π^0 multiplicity is proportional to the number of participants [6,7]. The dependence of the multiplicity of secondary particles, created when the π meson propagates through the medium, can be expressed as [24]

$$M_x \propto \int_{\vec{r}} \int_{\vec{p}} f_\pi(\vec{r}, \vec{p})\,(1 - e^{-D(\vec{r},\vec{p})/\lambda})\, d^3\vec{r}\, d^3\vec{p}\,, \quad (1)$$

where $f_\pi(\vec{r}, \vec{p})$ is the π phase-space density in the source, $D(\vec{r}, \vec{p})$ is the distance traveled by pions in matter, and λ is the mean free path of pions in nuclear matter. Assuming that π mesons are radially emitted from a homogeneous and spherical source of radius R, we obtain

$$M_x \propto \{\xi^3 - 3[\xi^2 - 2\xi + 2(1 - e^{-\xi})]\}, \quad (2)$$

where $\xi = (R/\lambda)$. For a light system ($\xi < 1$) the multiplicity of secondary particles is proportional to $\xi^4 \sim A_{\rm part}^{4/3}$. This result qualitatively explains the enhancement of high m_t π^0 as a function of the reaction centrality with respect to the overall π^0 multiplicities (Fig. 3). A more quantitative comparison can be achieved by calculating the average number of participants corresponding to a given $M_{\rm SD}$ as [25] $\langle A_{\rm part}(M_{\rm SD})\rangle = M_{\pi^0}(M_{\rm SD})/P_{\pi^0}^{\rm inc}$, where $M_{\pi^0}(M_{\rm SD})$ is the π^0 multiplicity and $P_{\pi^0}^{\rm inc}$ is the π^0 probability per number of participants [26]. We observe that the $\langle A_{\rm part}\rangle^{4/3}$ dependence predicted by this geometrical model reproduces quite well the dependence of the high m_t pions with the reaction centrality (Fig. 3). This result highlights the role of high order processes for the production of energetic particles beyond the nucleon-nucleon kinematical limit in an excited nuclear medium.

The Dubna cascade model (DCM), which contains all elementary processes leading to the production of γ, π, and η mesons in nuclear matter, provides a good description of the π and η meson production at relativistic energies [4] and π production at intermediate energies [5]. For the system Ar + Ca at 180A MeV, this model gives a η meson cross section 1 order of magnitude lower than the measured upper limit (see Table II) and an inverse slope of the m_t distribution of the π^0 that is 12% lower than the measured one. The DCM model predicts the process $\pi + N \rightarrow \eta(\pi) + N$ to be the main mechanism at the origin of the high m_t π^0 and η mesons.

In summary, the production of π^0 and η mesons, measured at the same bombarding energy and below their respective threshold energy, has been studied in the

TABLE I. Experimental results for the production of neutral mesons, π^0 and η, in the reaction Ar + Ca at 180A MeV. The rapidity range covered, Δy, is $0.26 < y/y_{\rm beam} < 0.71$. T is the exponential inverse slope of the m_t distribution from 180 to 400 MeV. Errors include statistical and systematic errors coming from combinatorial background subtraction, from reaction efficiency of the start detector, and from the extrapolation to 4π.

Meson	$M^{\Delta y}$	$\sigma^{\Delta y}$ (mb)	T (MeV)	$\epsilon^{4\pi}$	$M^{4\pi}$	$\sigma^{4\pi}$ (mb)
π^0	$1.40(0.15) \times 10^{-3}$	3.6(0.3)	24(1)	1.2×10^{-2}	$5.8(1.0) \times 10^{-3}$	15(3)
η	$\le 7.6(4.0) \times 10^{-9}$	$\le 1.9(1.0) \times 10^{-5}$	$\cdots$	0.50×10^{-2}	$\le 1.7(0.8) \times 10^{-8}$	$\le 4.4(2.2) \times 10^{-5}$

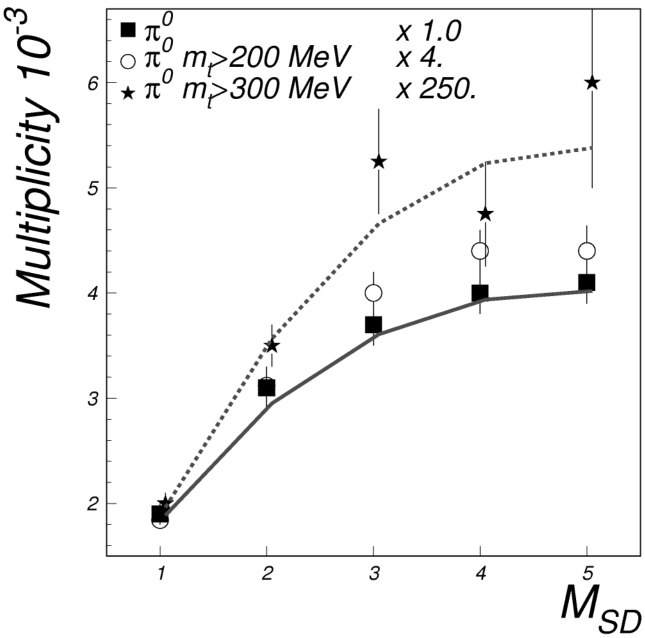

FIG. 3. Multiplicity of π^0 and high m_t π^0 as a function of the number of detected particles in the SD, normalized at $M_{\mathrm{SD}} = 1$. The solid line is proportional to A_{part} and the dashed line proportional to $A_{\mathrm{part}}^{4/3}$.

system Ar + Ca at 180A MeV. The η-production cross section is found to be much smaller than expected from the scaling relation of meson production using the free NN threshold energy. The π^0 m_t distribution extends well beyond the kinematical limit ($E_{\max} = 300$ MeV). A deviation from a pure exponential behavior has been observed. Finally, π^0 multiplicities have been studied as a function of the nuclear reaction centrality. The ratio of the high m_t π^0 multiplicity to total multiplicity increases with the number of participants proportionally to $A_{\mathrm{part}}^{1/3}$. This dependence suggests that high m_t π^0 are produced in secondary collisions of the primordial pions with nucleons. Finally, the experimental results have been confronted with the DCM calculations, which can produce energetic particles beyond the kinematical limit through secondary processes involving the primordial pions.

We would like to thank the GSI technical staff for their help and delivery of the high quality Ar beam required for the present measurement. This work was in part supported by the IN2P3, France, by the CEA, France, by the FOM, The Netherlands, by the DGICYT, Spain, by the Generalitat Valenciana, Spain, by the BMBF, Germany, by the DFG, Germany, by the GACR, Czech Republic, and by the the European Union HCM network Contract No. HRXCT94066.

TABLE II. Calculated values of the meson ratio and the inverse slope of the m_t π^0 distribution obtained the Dubna cascade model [5].

	DCM	Present data
$\sigma_\eta/\sigma_{\pi^0}$	3×10^{-7}	$\leq 3.0(1.5) \times 10^{-6}$
T (MeV)	21	24(1)

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